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Late-time X-ray Brightening vs. Early Double-peaked Balmer Emission: Investigating Disk Formation in the TDE AT2020nov

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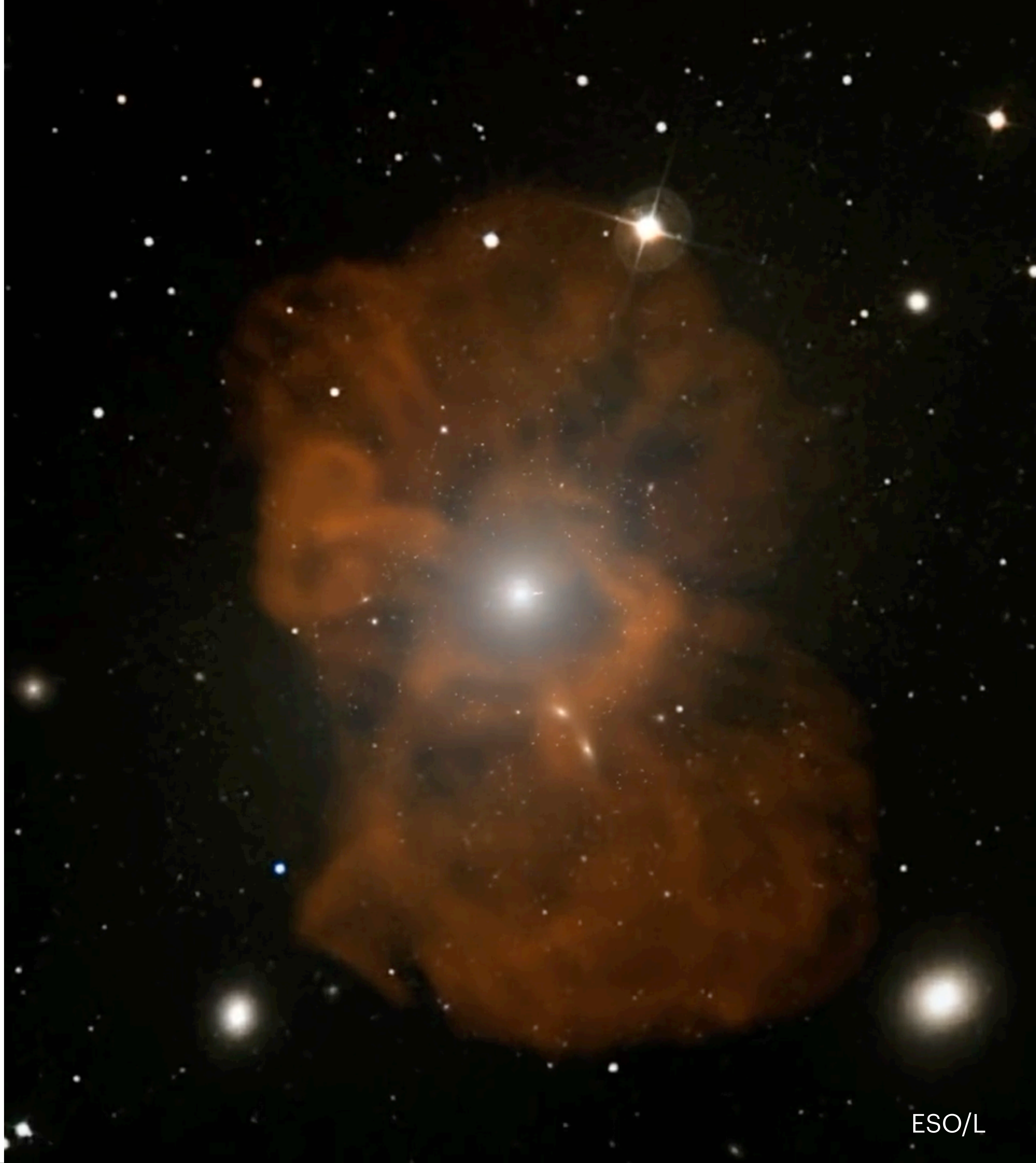
Black Holes

Massive and common

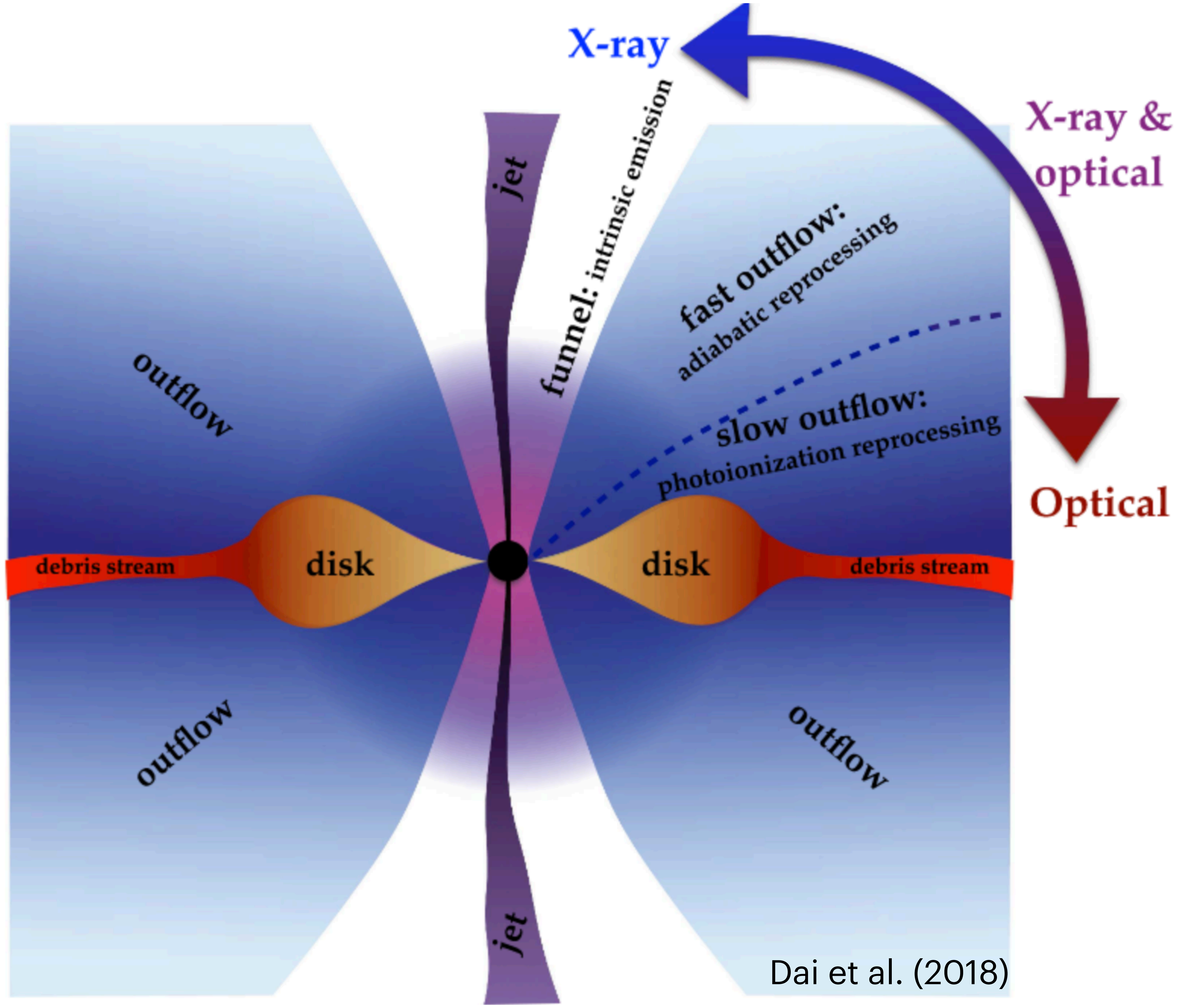
- **Ubiquitous** in galactic nuclei above a certain mass; play fundamental role in many astrophysical phenomena
- **Co-evolution** between black holes and host galaxies driven by feedback can alter interstellar medium and star formation rates.
- Brightest steady electromagnetic radiation sources in the universe, but origins are **unclear**.
- High-*z* observations of quasars and active galactic nuclei (AGN) challenge current theoretical models of formation.
- Black hole evolution and growth history is **uncertain**.
- "Solvable problem" using distribution of present universe's low-mass black holes and spin.



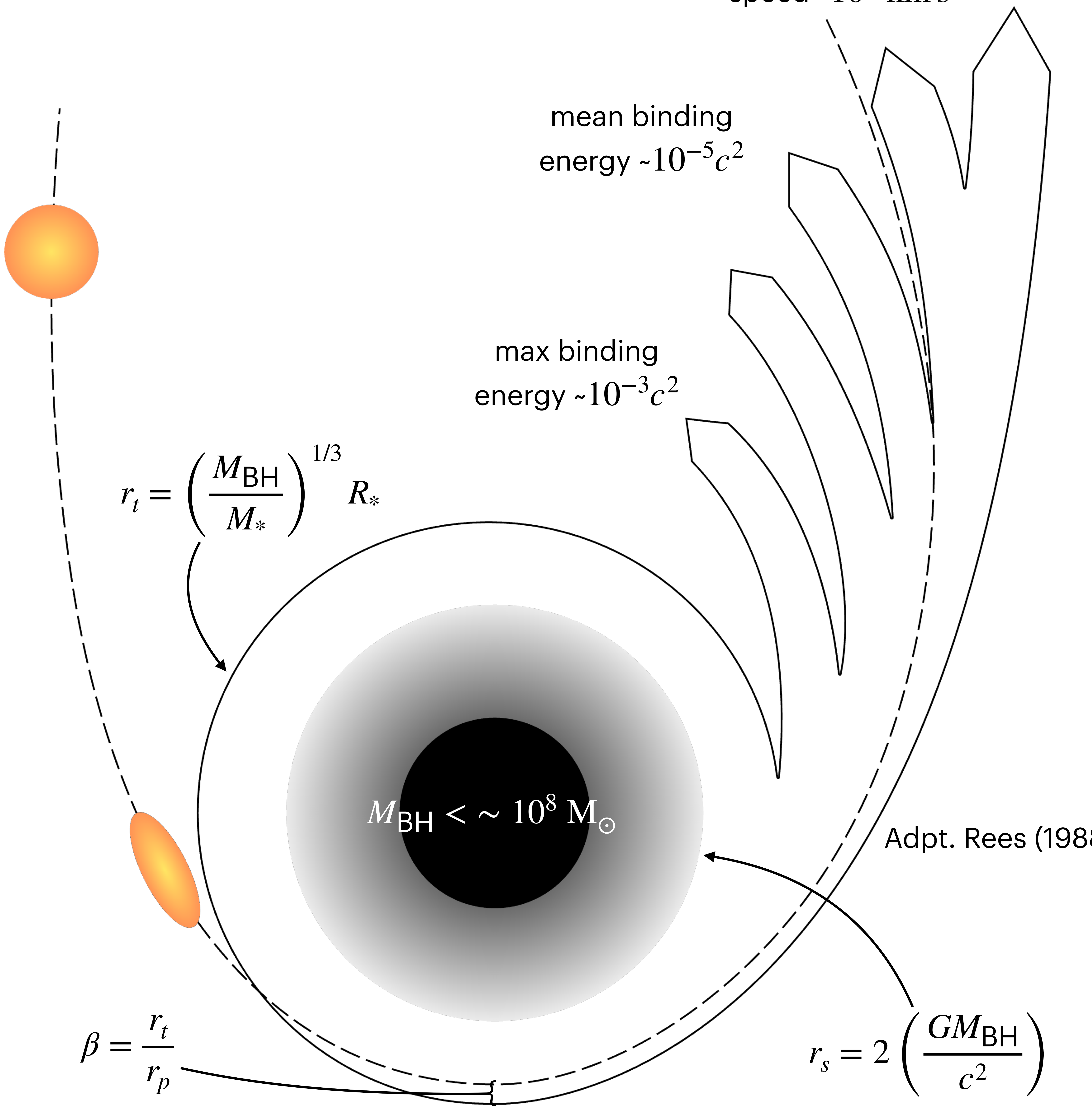
ESO/L

Tidal Disruption Events

Tracers of BH demographics



Dai et al. (2018)



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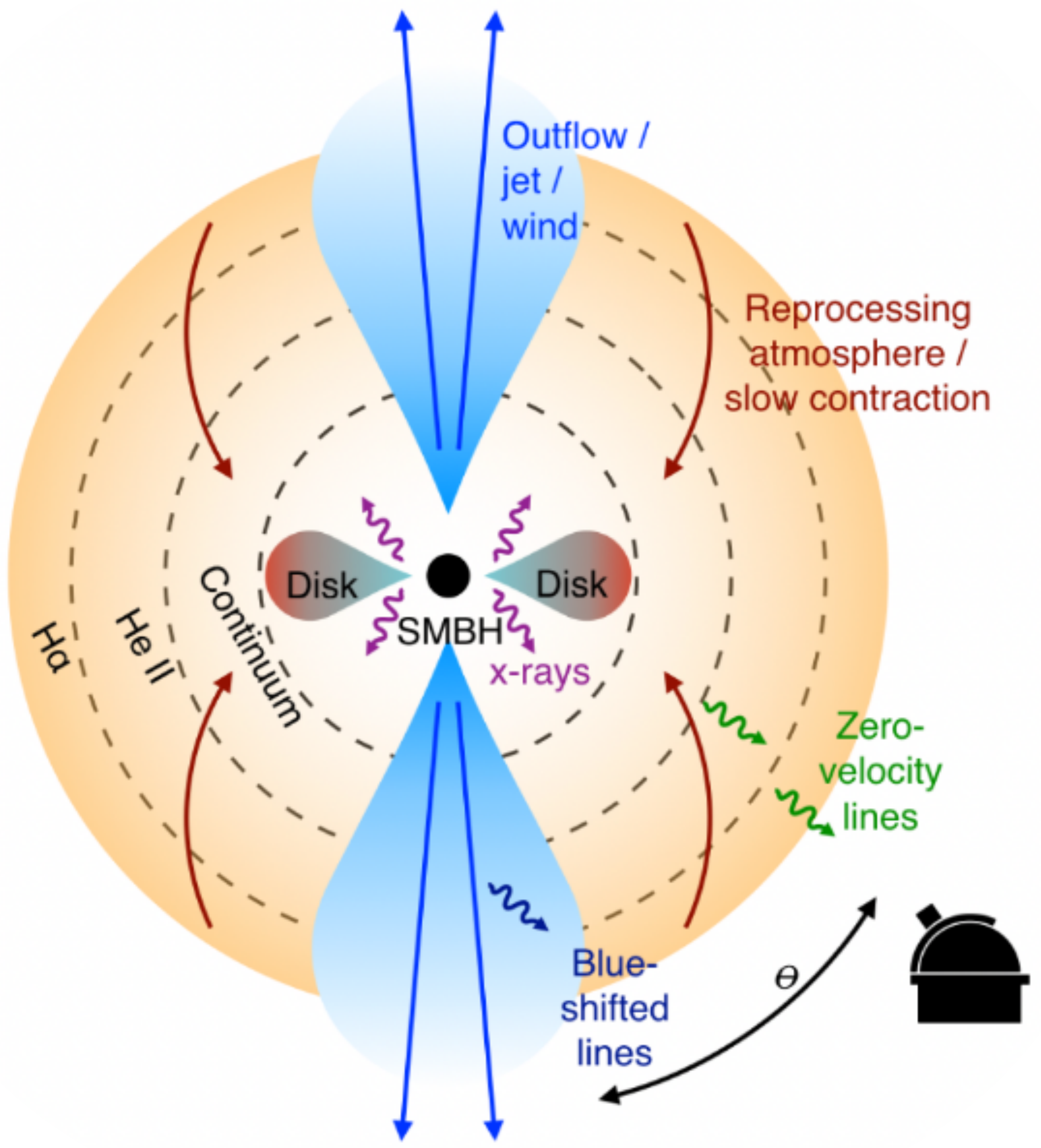
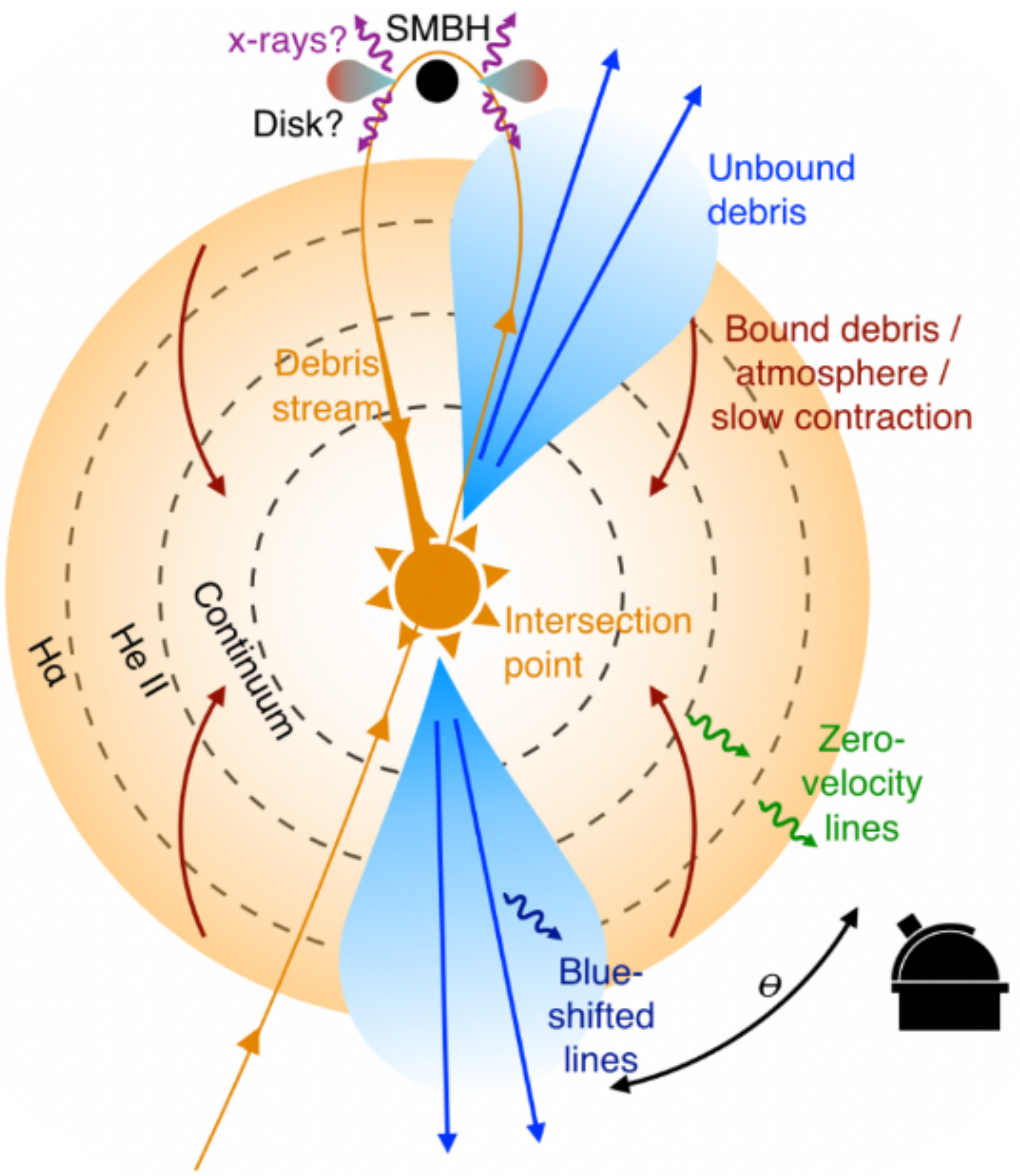


Formation of accretion disk from the bound debris.

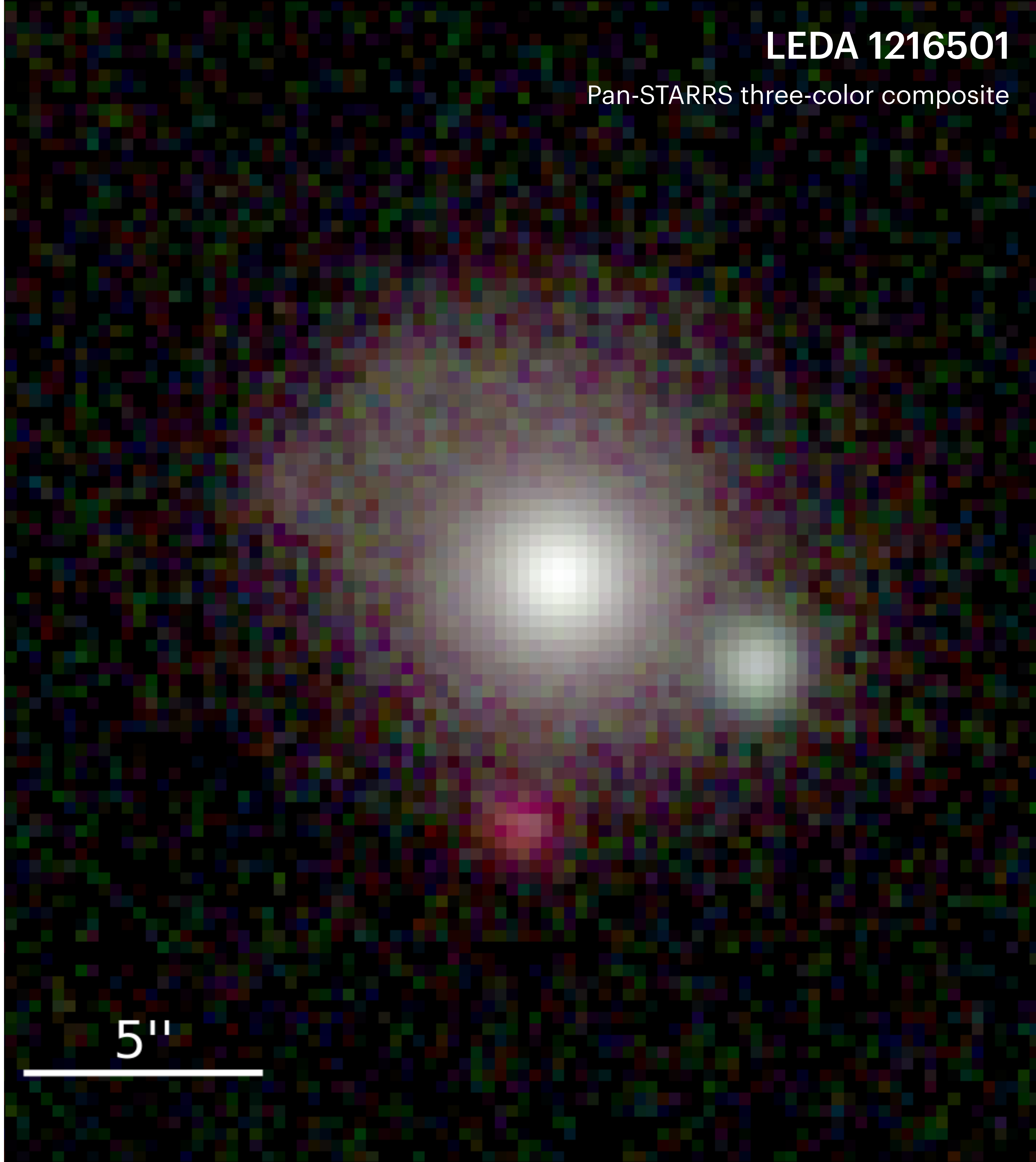
Emission from shocks produced from colliding debris streams.

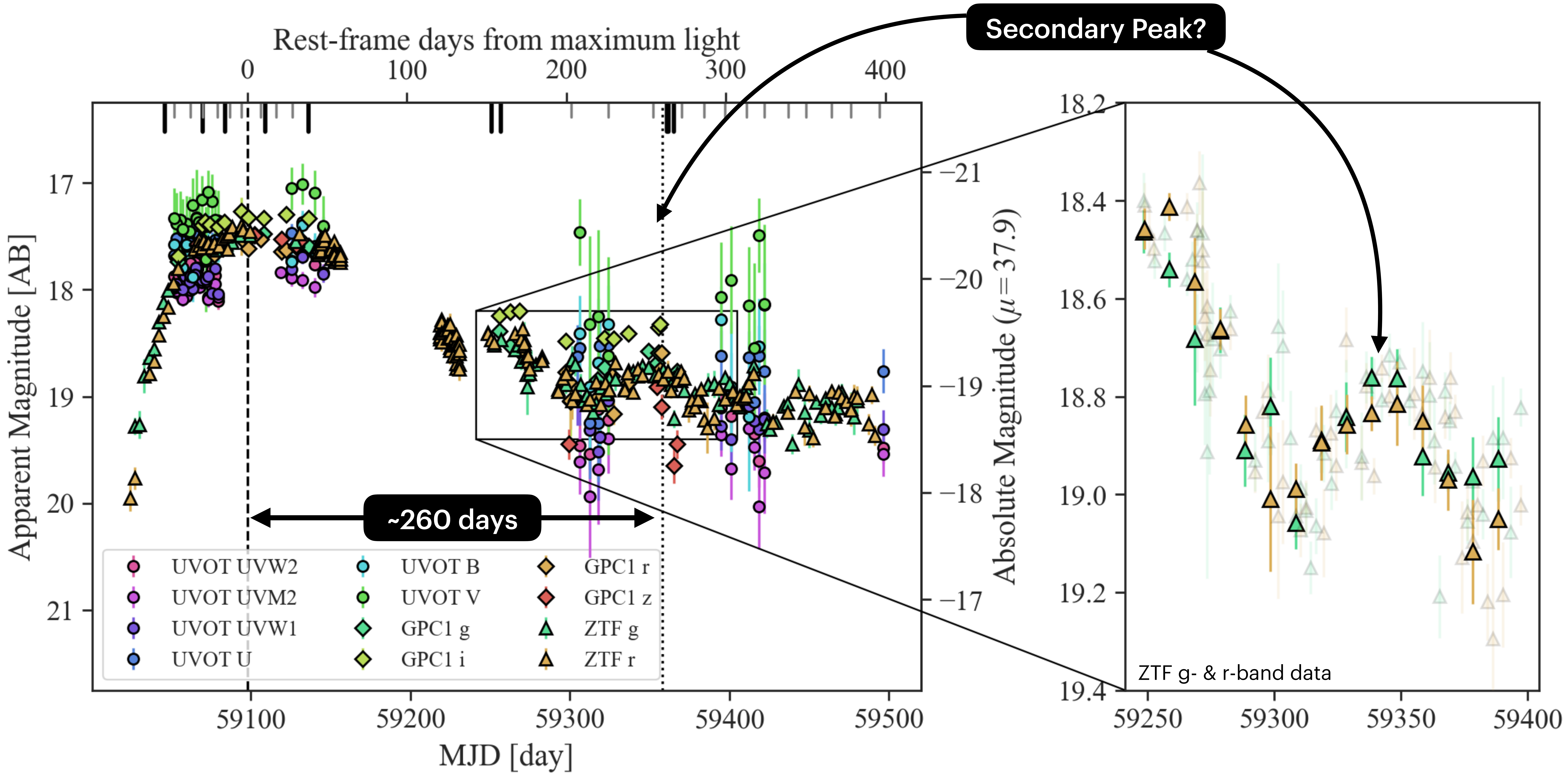


Short et al (2020)

TDE Candidate AT2020nov
Discovery and observations

- Discovered June 27th, 2020
- ZTF magnitude of g = 19.67
- Redshift of ~0.08, distance of ~390 Mpc
- Announced by ALeRCE with identified by YSE
- Strong He II emission on follow-up (20 days after discovery)
- WISE color of host not clearly AGN-like

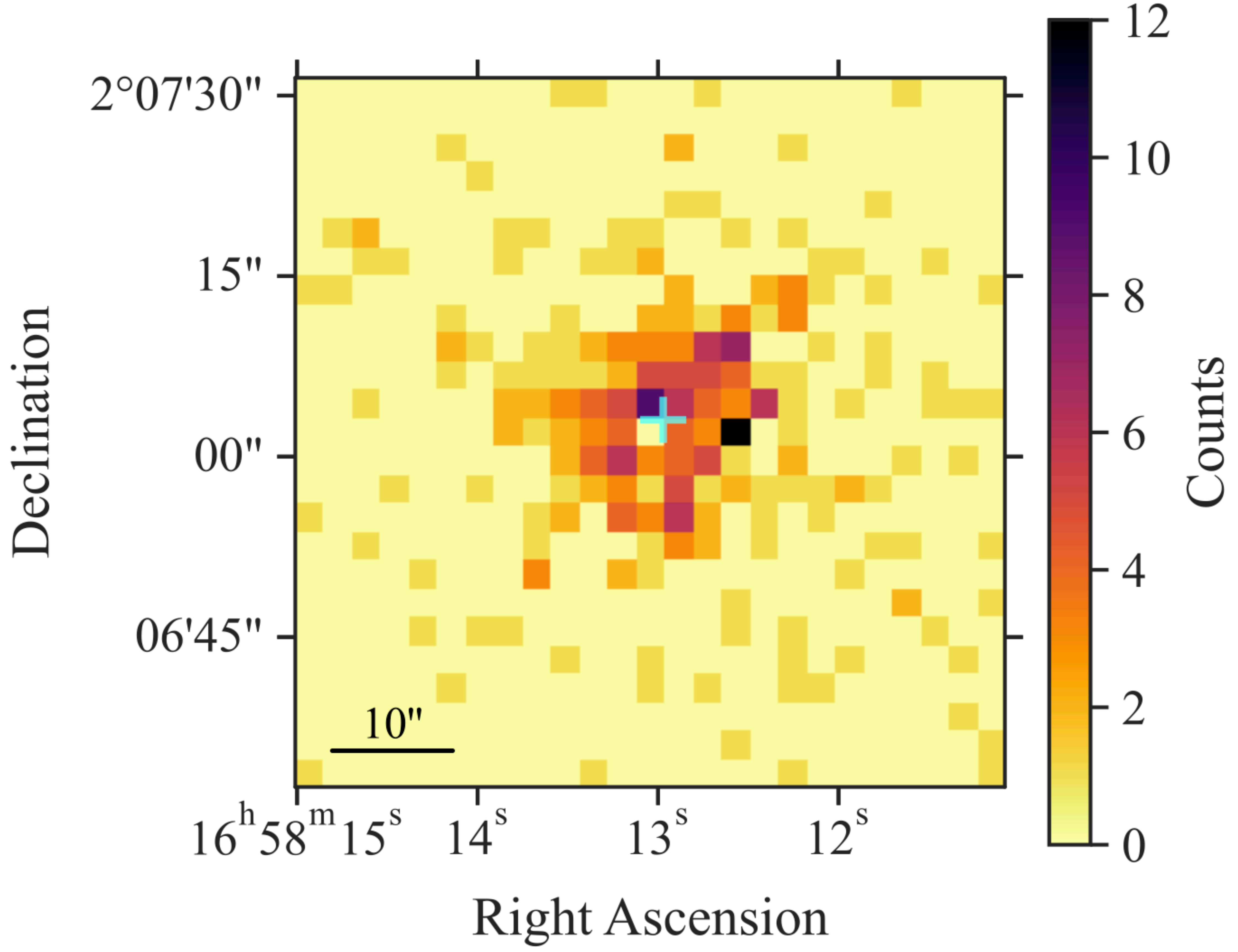


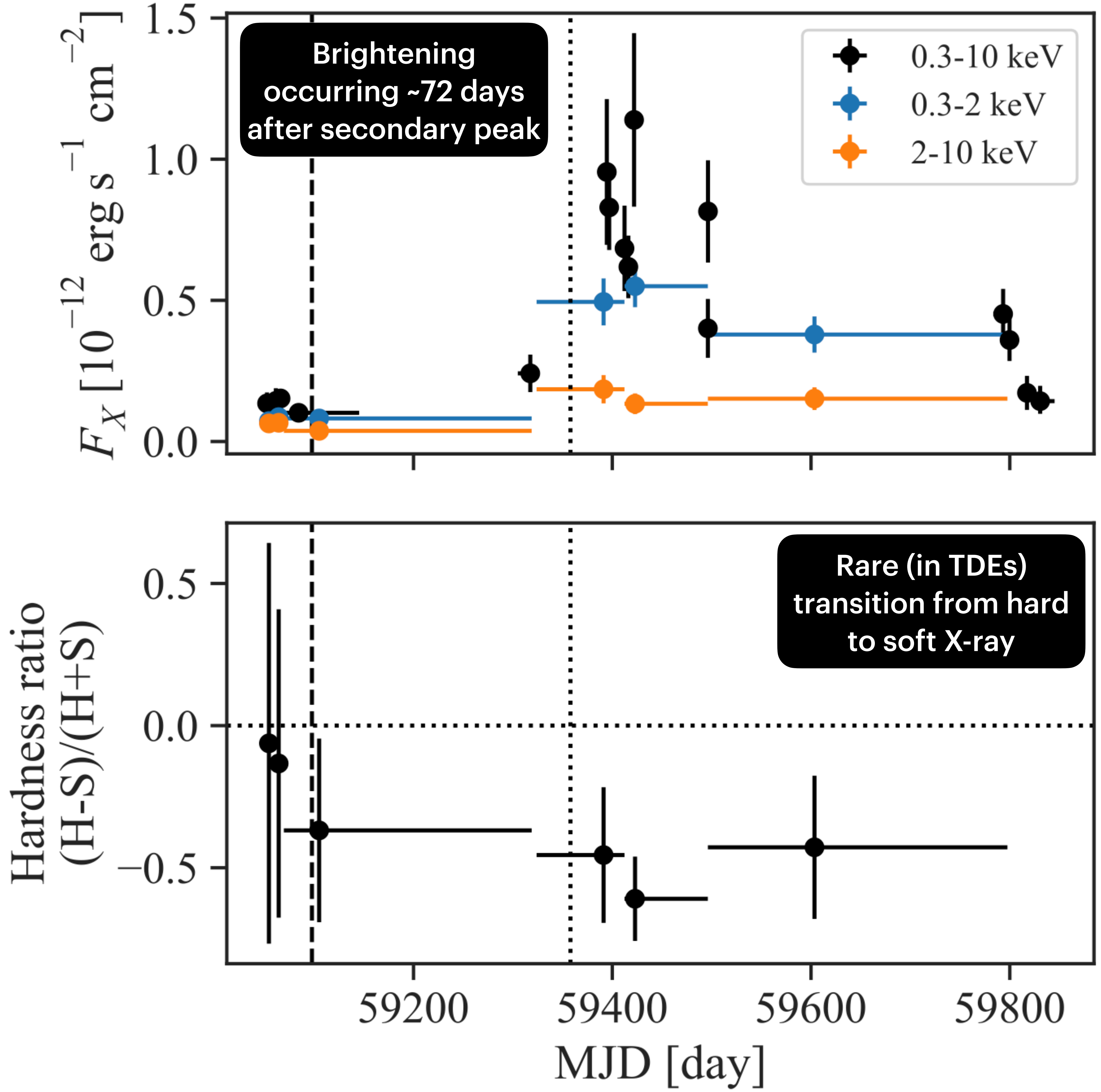


Secondary Peak?
Rest-frame days from maximum light
0
100
200
300
400
17
18
19
20
21
Apparent Magnitude [AB]
−21
−20
−19
−18
−17
Absolute Magnitude (μ=37.9)
~260 days
UVOT UVW2
UVOT UVM2
UVOT UVW1
UVOT U
UVOT B
UVOT V
GPC1 g
GPC1 i
GPC1 r
GPC1 z
ZTF g
ZTF r
59100
59200
59300
59400
59500
MJD [day]
18.2
18.4
18.6
18.8
19.0
19.2
19.4
ZTF g- & r-band data
59250
59300
59350
59400

X-ray Analysis

Late-time emission

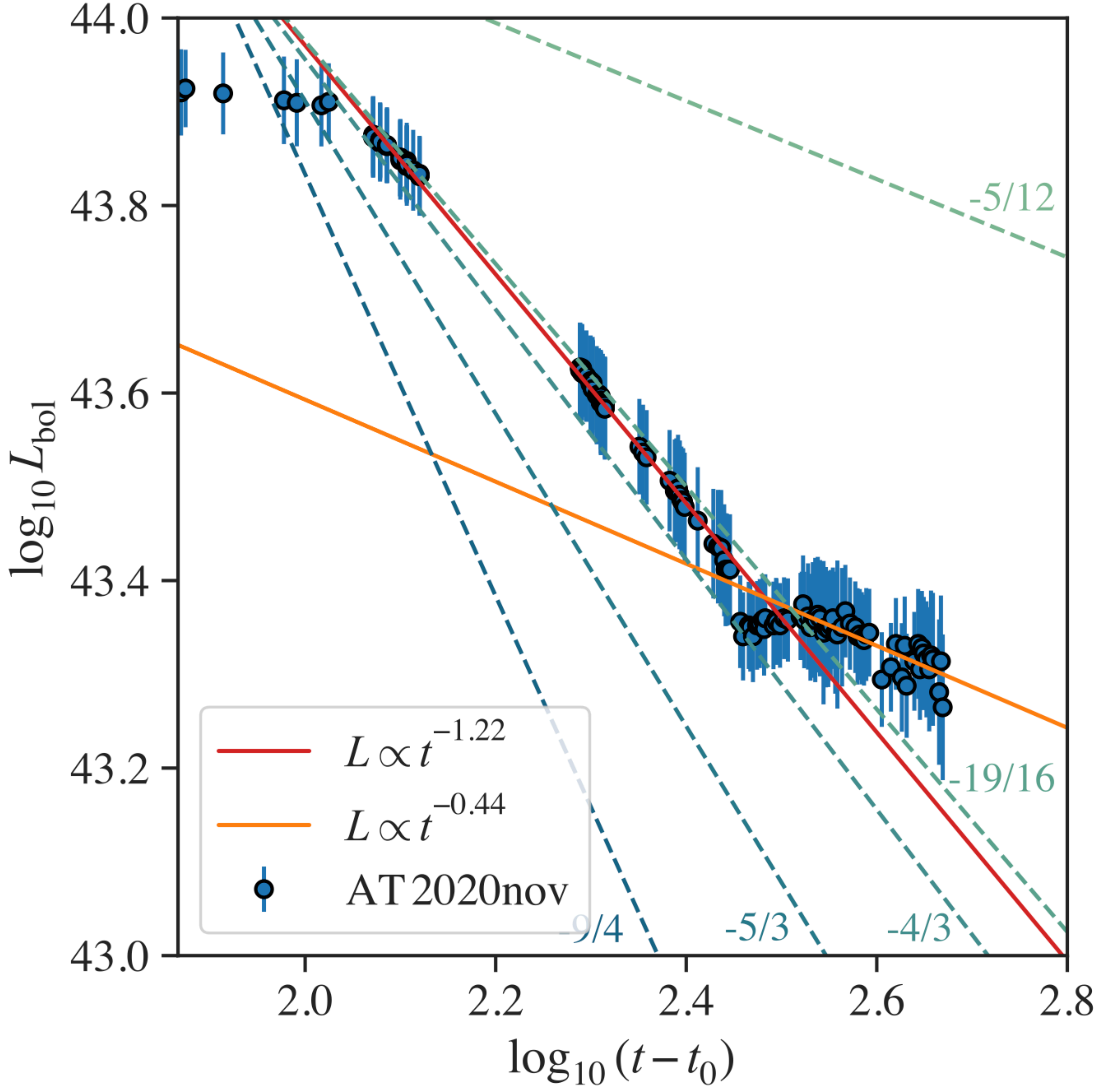




Fallback Rates

Accretion transition at late times

- Much shallower than the expected $t^{-5/3}$ fallback rate expected from analytical arguments
- Clear difference in late-time fallback behavior
- Initially consistent with viscous disk accretion around a large ($> 10^7$ $M_\odot$) SMBH (Arcavi et al. 2014)
- Late-time behavior similar to disk emission



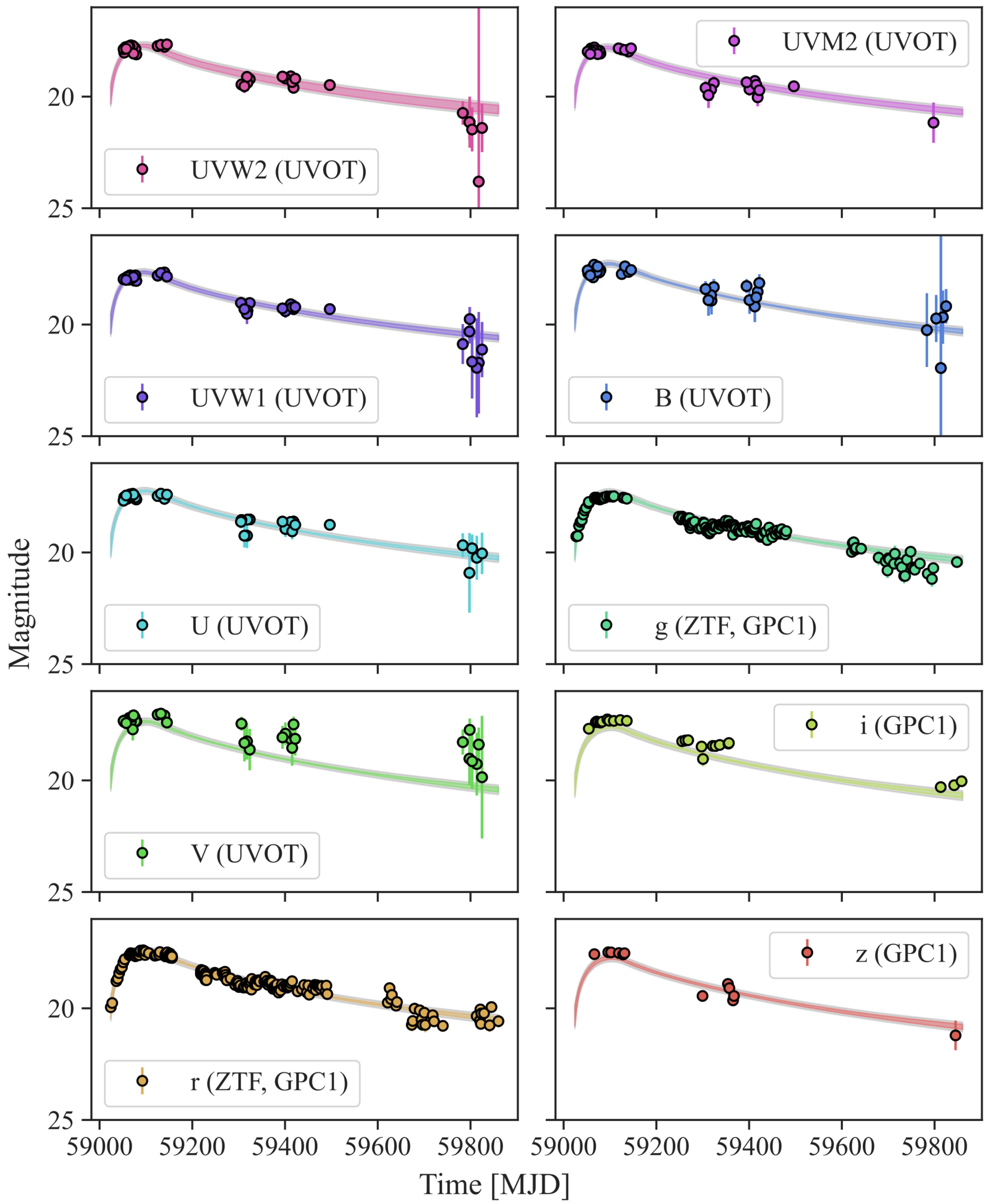
Light Curve Fitting

Parameters of disruption

Parameter	Prior	Posterior	Units
$\log R_{\mathrm{ph},0}$	[-4, 4]	$0.479^{0.069}_{-0.056}$	
$\log T_v$	[-3, 5]	$-0.185^{0.724}_{-1.282}$	d
β	[0, 2]	$1.098^{0.059}_{-0.051}$	
$\log M_h(M_\odot)$	[5, 8]	$7.168^{0.052}_{-0.064}$	$M_\odot$
$\log \epsilon$	[-2.3, -0.4]	$-1.005^{0.193}_{-0.146}$	
l_{ph}	[0, 4]	$0.801^{0.047}_{-0.051}$	
$\log n_{\mathrm{H,host}}$	[16, 23]	$21.107^{0.029}_{-0.044}$	cm^{-2}
M_*	[0.01, 100]	$0.290^{0.100}_{-0.113}$	$M_\odot$
t_{exp}	[-500, 0]	$-14.792^{2.161}_{-2.557}$	d
$\log \sigma$	[-4, 2]	$-0.682^{0.017}_{-0.016}$	

Estimated disruption time:

$$t_0 = (-14.8\ \mathrm{d}) + (-73.5\ \mathrm{d}) = -88.3\ \mathrm{d}$$



MOSFiT, Guillochon et al (2018)

SMBH Mass

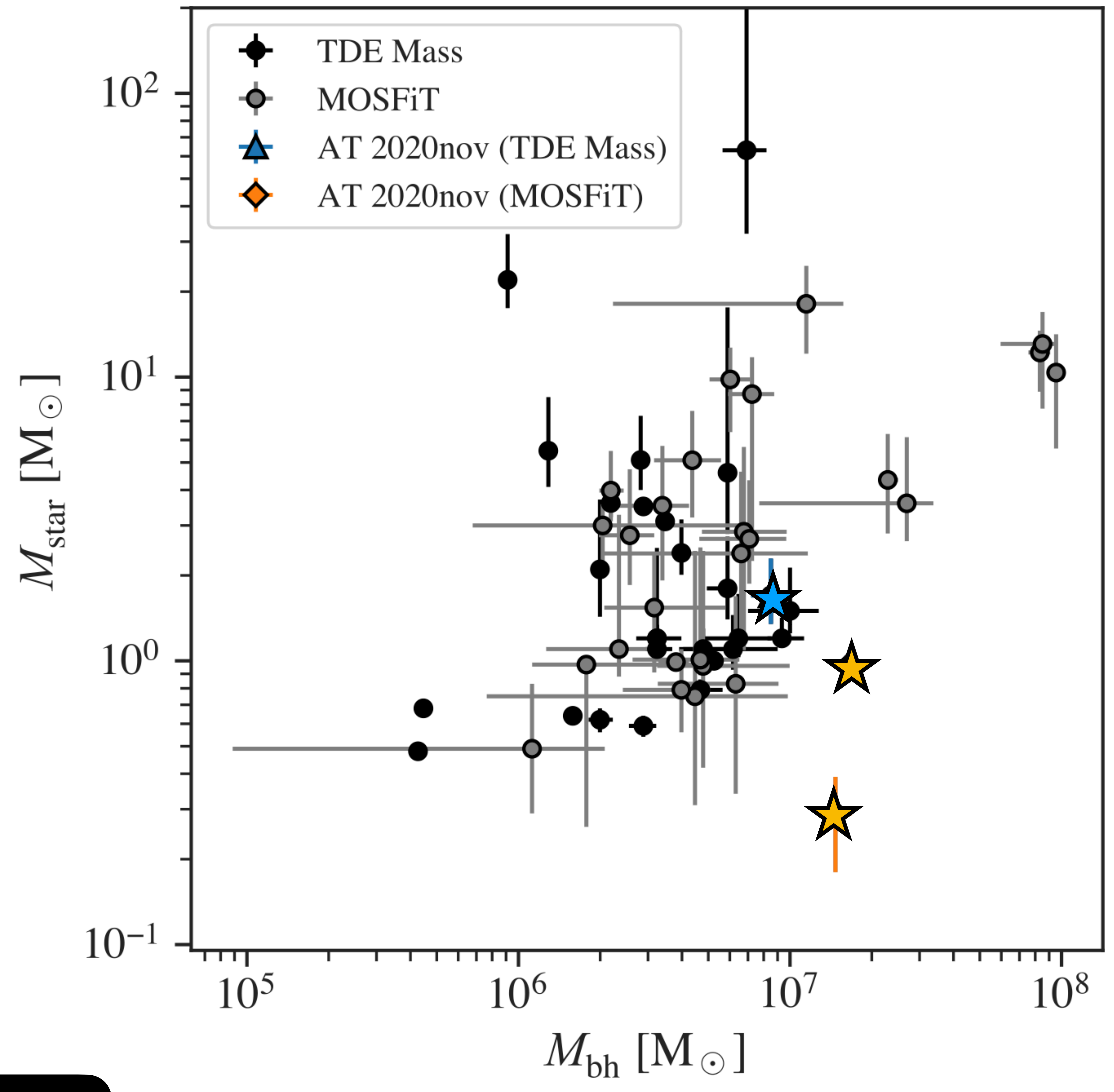
Comparing estimates

Assumes fallback from accreting material

	$\log M_{\rm BH}$	$M_{\rm star}$
MOSFiT (Full)	$7.17^{+0.05}_{-0.06}$	$0.29^{+0.10}_{-0.11}$
MOSFiT (Primary)	7.22 ± 0.04	$0.96^{+0.06}_{-0.12}$
TDEMass	$6.93^{+0.05}_{-0.07}$	$1.7^{+0.35}_{-0.59}$
$M_{\rm BH}$–σ	7.20 ± 0.56	
$M_{\rm BH}$–M_*	7.53 ± 0.62	

Mockler et al. (2019)
Ryu et al. (2020)
pPXF (Cappellari 2022), Kormendy & Ho (2013)
Reines & Volonteri (2015)

Emission from debris stream collisions

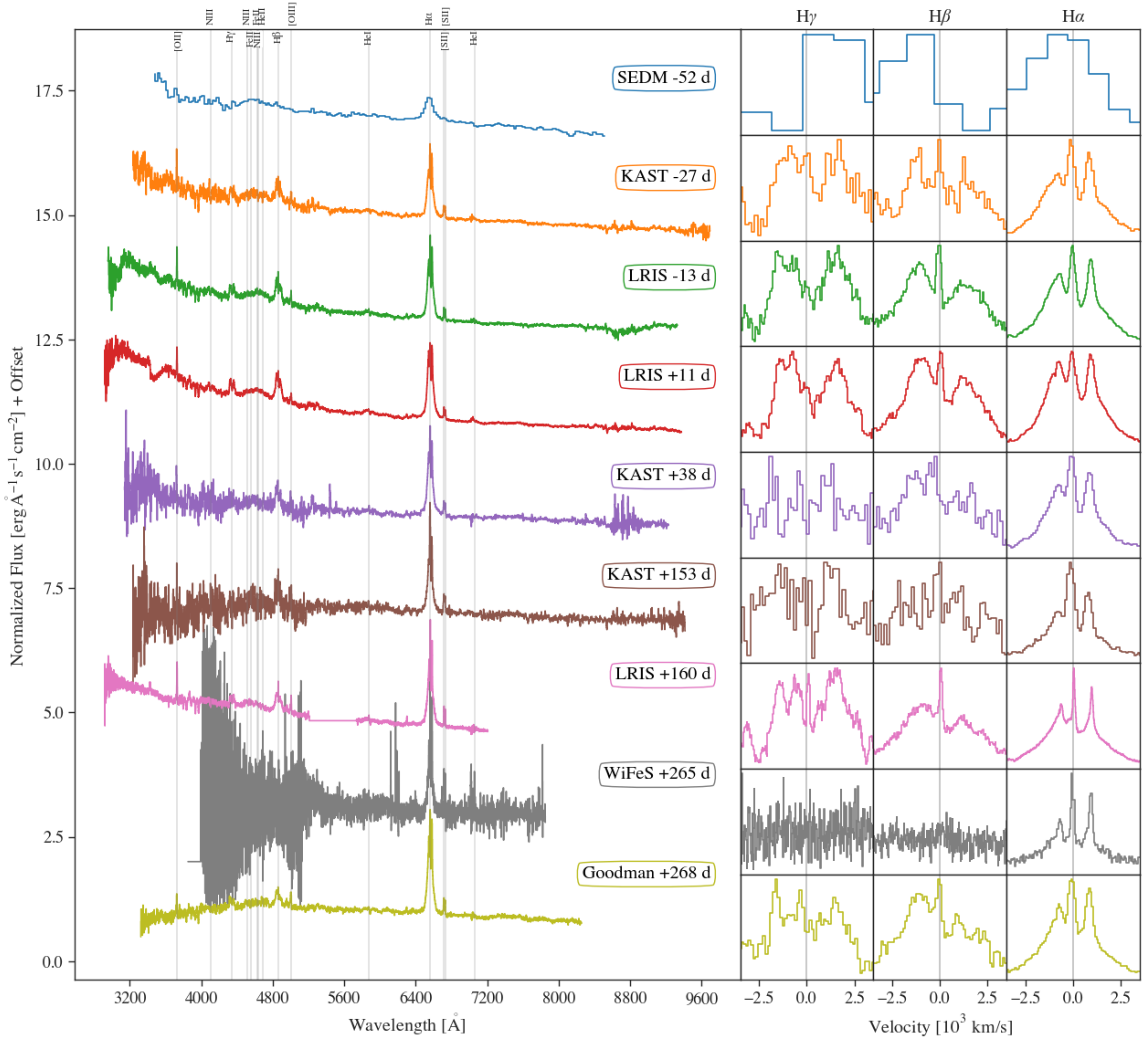


Sample comparison with Hammerstein (2022)

Spectroscopy

The other side of the story

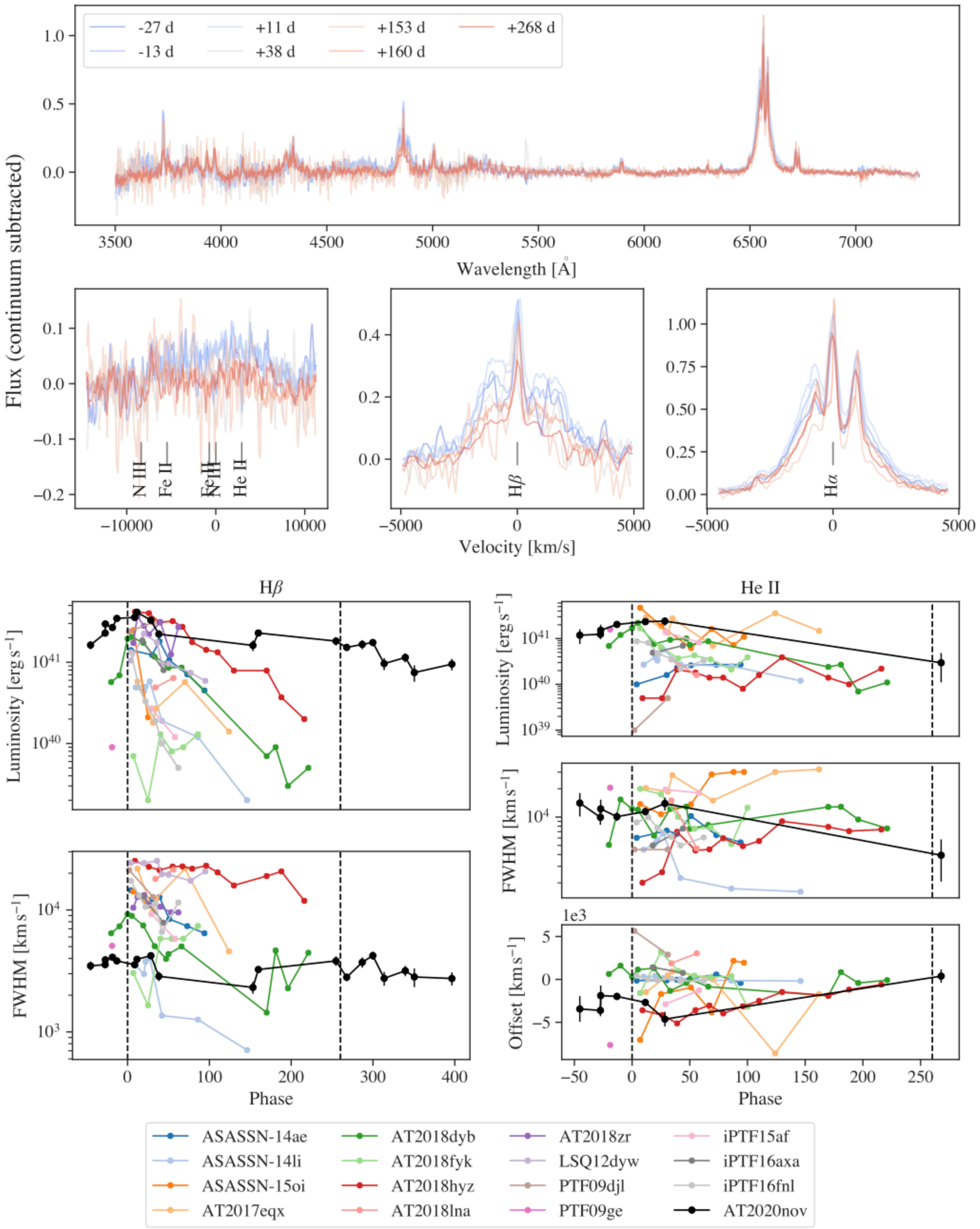
- Obtained 8 spectra across 4 instruments over ~1 year of observing
- Clear signs of **early** double-peaked Balmer features
- May be the consequence of a bi-polar outflow, or **disk formation** as early as 27 days before peak
- Contradicts stream collision/shock model favored by pure photometry observations



Emission Lines

Evolution of broad features

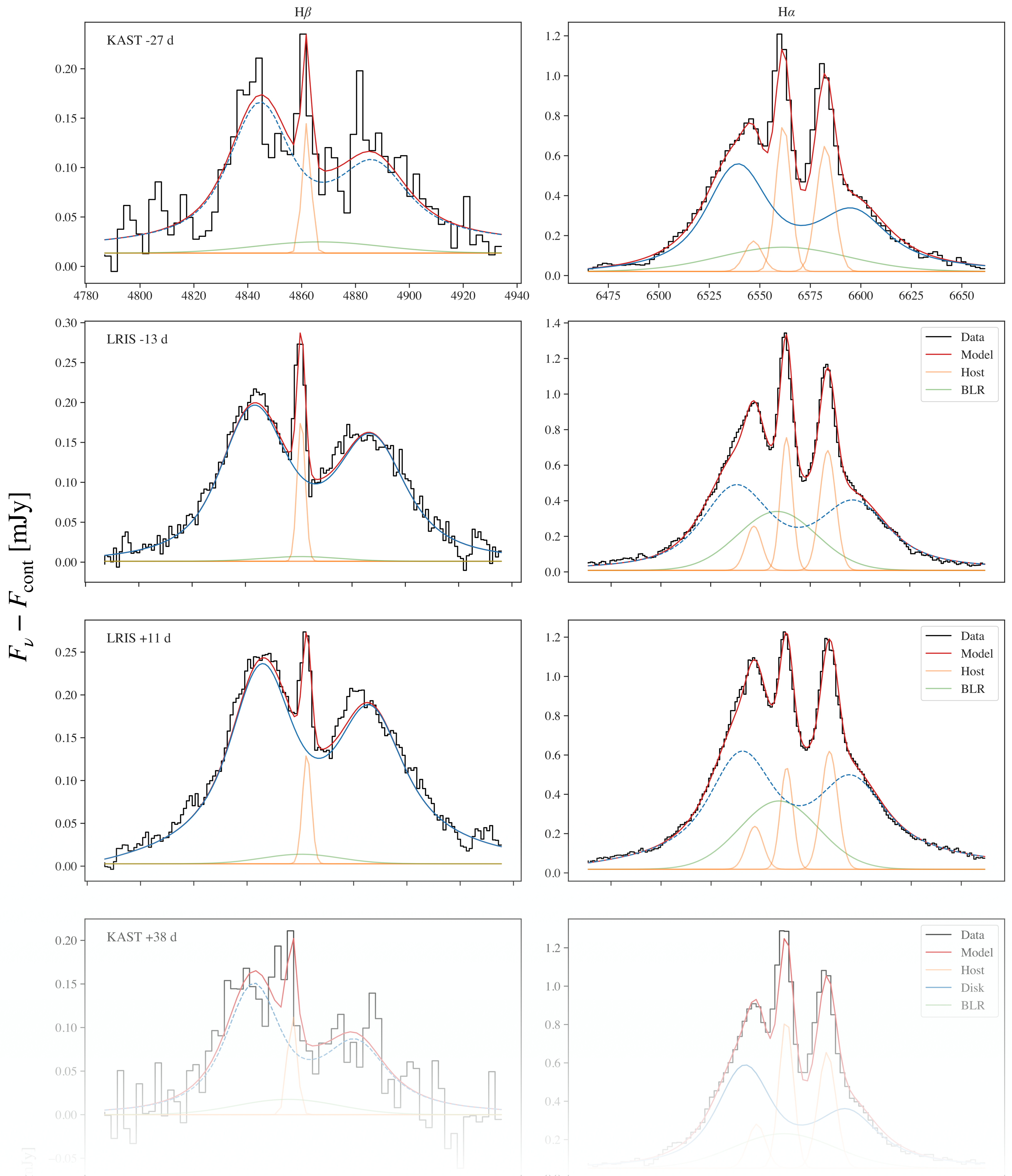
- Double-peaked Balmer profiles are well-formed at least 27 days before optical peak
- Suggest fast, efficient disk formation
- No significant evolution in FWHM of Balmer lines, suggesting their origin is not from an optically thick wind or outflow
- Widths do not grow over time, indicating we're not looking at an AGN



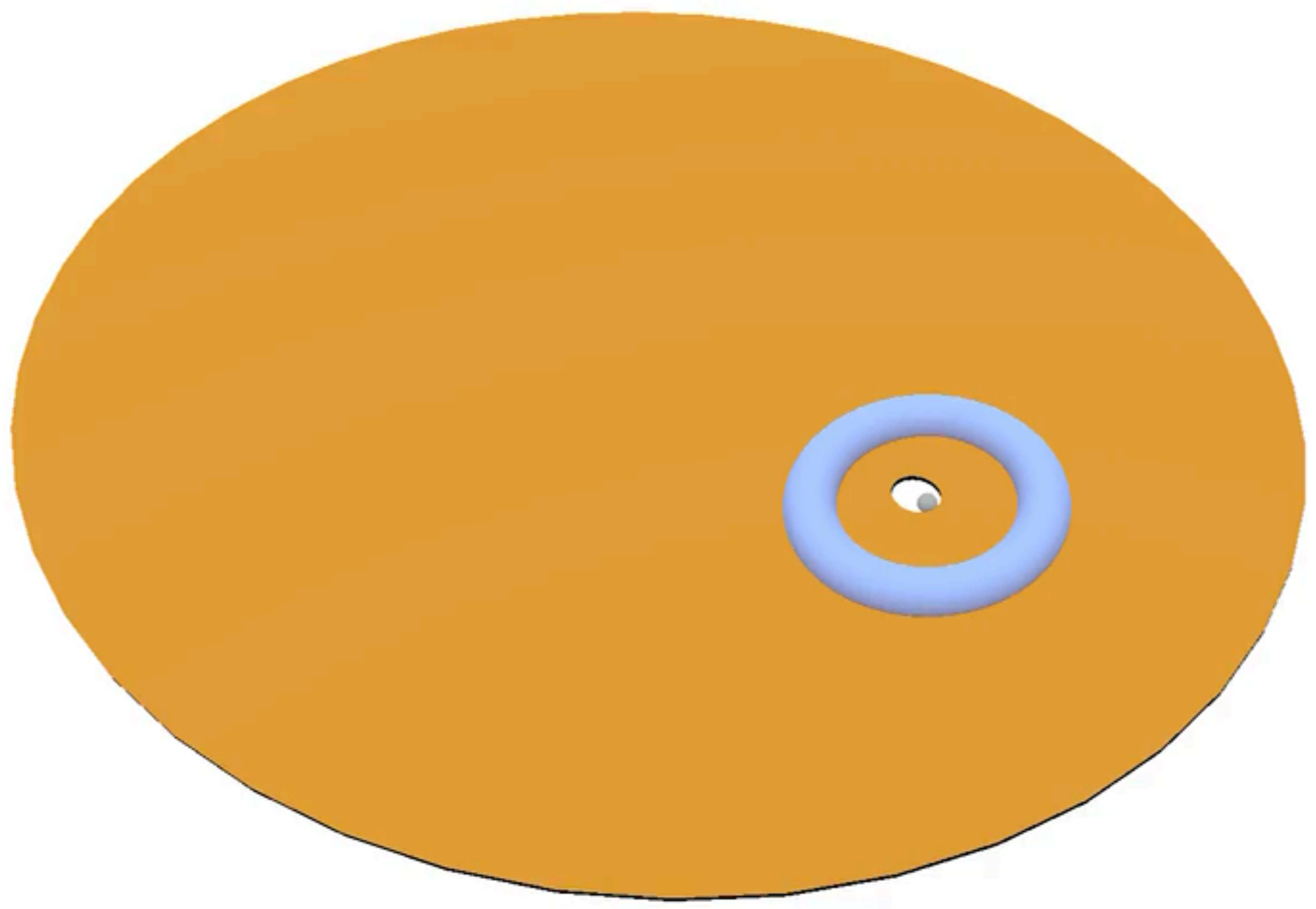
Disk Modeling

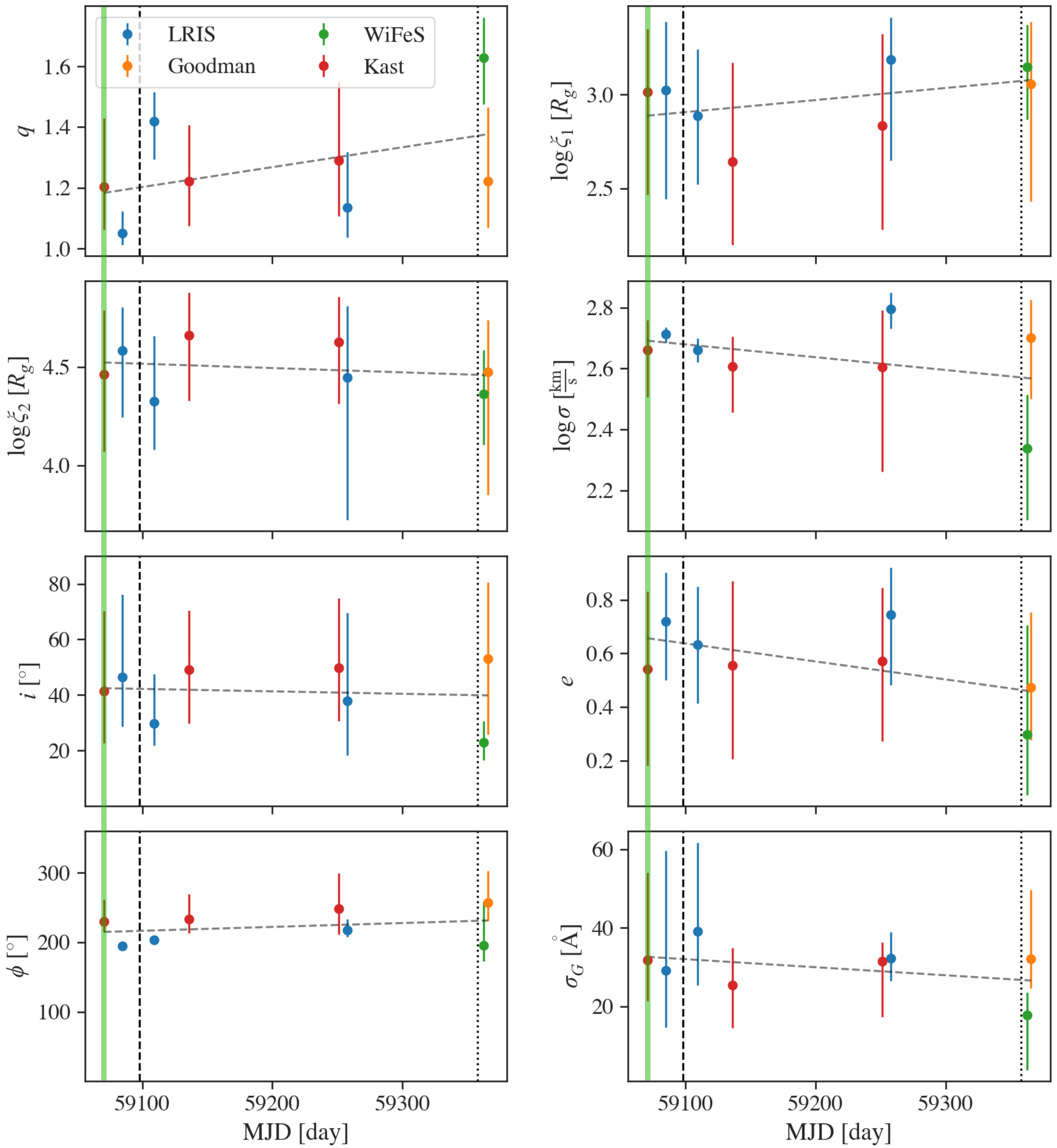
Geometric constraints on formation

- Relativistic accretion disk model fitting to double-peaked Balmer emission can define characteristics of accretion disk
- Favor single emission line fitting to avoid host contamination
- Include presence of a broad line region, common in other double-peaked TDE fitting (AT2018hyz, etc)



Days since first observation: 46.34



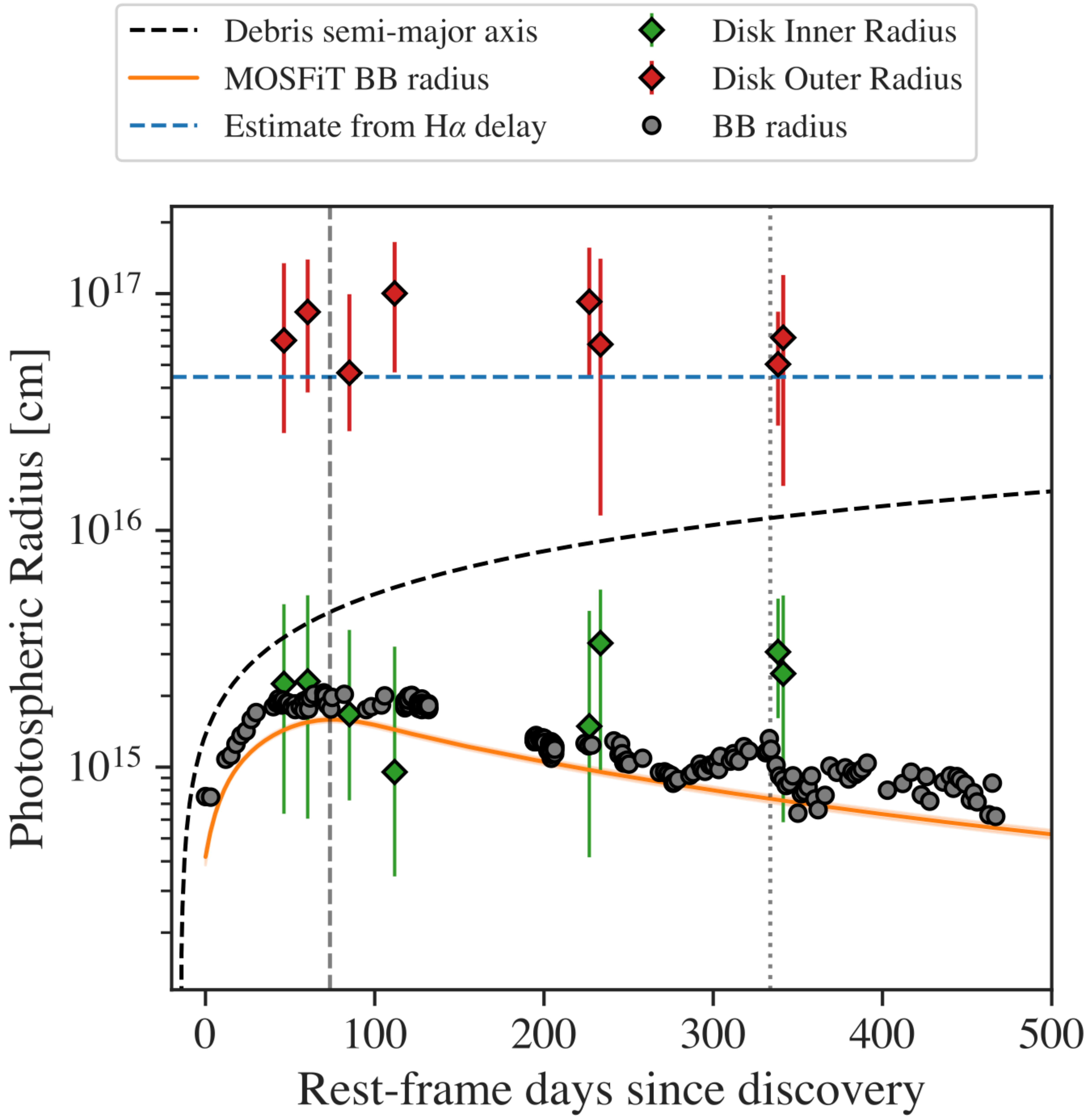


Loose bounds on disk outer radius

Photospheric Radii

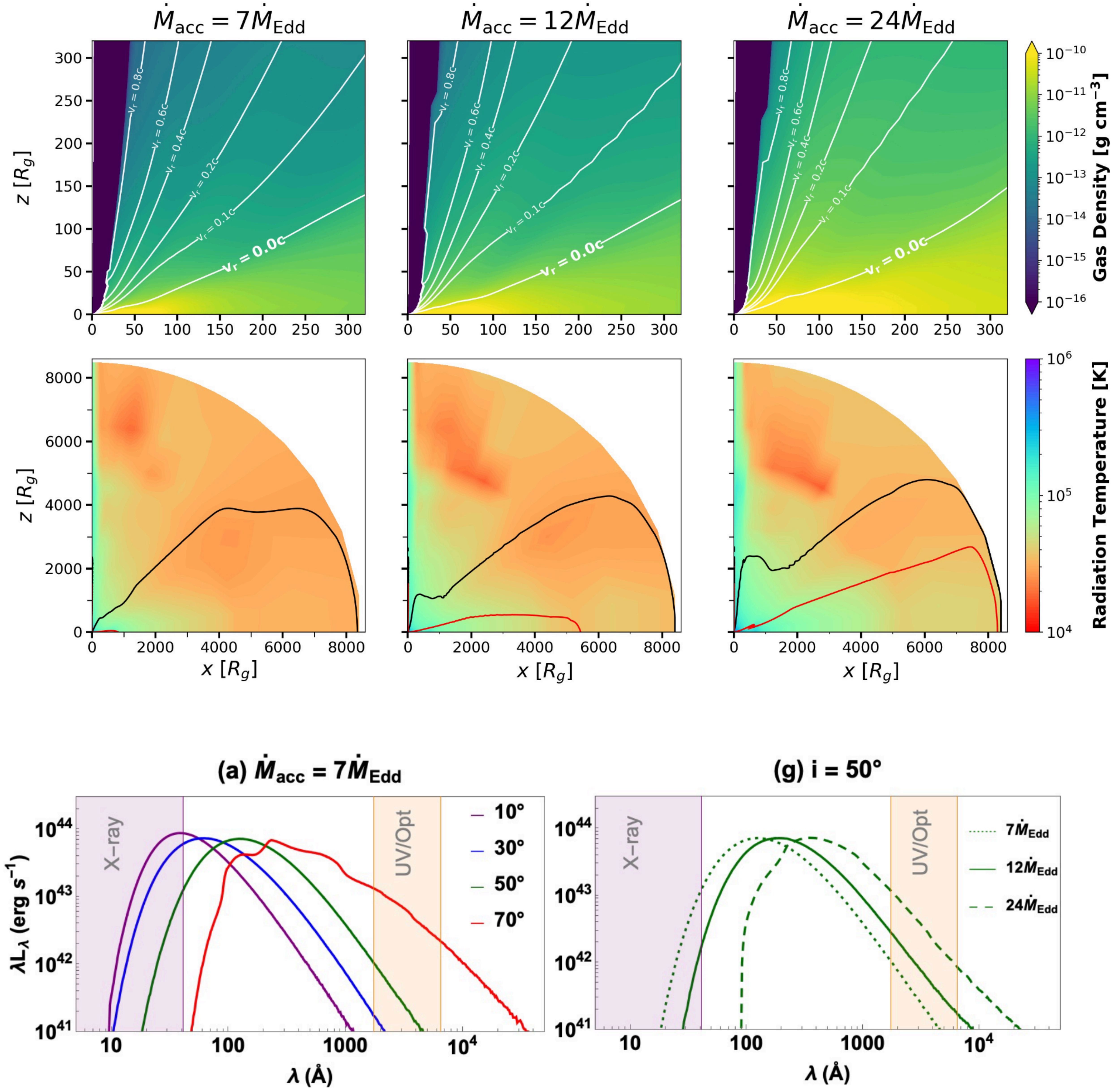
Comparing emission locations

- Does not seem to follow the semi-major axis of the orbits of returning stellar debris based on Keplerian motion
- Large radius is consistent with velocity difference of double-peaks
- Separated material from fast circularization of debris streams
- Time-lag analysis of $\mathrm{H}\alpha$ indicate that the line emitting region is much farther out (Roth 2016, Charalampopoulos 2022)
- Delay in $\mathrm{H}\alpha$ could be consequence of recombination



Disk Structure
Geometric considerations

- Early-time evolution could be dominated by a dense, geometrically thick accretion disk
- Prevents X-ray emission at intermediate angles until late-times when the “funnel” opens (Dai et al. 2018)
- Time-lag analysis of $\mathrm{H}\alpha$ indicates large radii difficult to explain with outflows, disk winds, or collision-induced outflow (CIO)
- Low density stellar material could be the reprocessing layer responsible for emission lines (Charalampopoulos 2022)
- Low $n_e \approx 1 - 5 \times 10^6\ \mathrm{cm}^{-3}$ can increase the recombination time



MHD simulations, Thomsen et al. (2022)

Reconciling Observations

Finding the narrative to explain what we see

	Shocks with late-time accretion	Early accretion with reprocessing	Pre-existing AGN disk with early-time shocks
Early disk	No prescription for early, well-formed disk formation		
First light curve peak	Stream-stream collisions		
Primary decay rate	Slow circularization?		
Second light curve peak	Accretion processes Consistent with X-ray brightening		
Secondary decay rate	Disk emission from delayed accretion		

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Early disk	No prescription for early, well-formed disk formation	Fast, efficient disk formation process	
First light curve peak	Stream-stream collisions	Primary accretion behavior, potentially thick reprocessing	
Primary decay rate	Slow circularization?	Viscous processes in disk material	
Second light curve peak	Accretion processes Consistent with X-ray brightening	Change in accretion behavior, or disk perturbations	
Secondary decay rate	Disk emission from delayed accretion	Disk emission from accretion	

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Finding the narrative to explain what we see

	Shocks with late-time accretion	Early accretion with reprocessing	Pre-existing AGN disk with early-time shocks
Early disk	No prescription for early, well-formed disk formation	Fast, efficient disk formation process	Pre-existing, but evolution of disk inconsistent
First light curve peak	Stream-stream collisions	Primary accretion behavior, potentially thick reprocessing	Stream-stream collisions
Primary decay rate	Slow circularization?	Viscous processes in disk material	Slow circularization?
Second light curve peak	Accretion processes Consistent with X-ray brightening	Change in accretion behavior, or disk perturbations	Accretion processes Consistent with X-ray brightening
Secondary decay rate	Disk emission from delayed accretion	Disk emission from accretion	Disk emission from delayed accretion